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Automated and Aluminum Welding Technology

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ABSTRACT

Automated welding technology and techniques for welding advanced aluminum alloys with potential for industrial and commercial applications have been developed by the National Aeronautics and Space Administration at the Marshall Space Flight Center. These technologies are being offered to private companies for commercial development, and include:

Variable polarity plasma arc welding, a welding process that produces high-quality aluminum welds for fabrication of the space shuttle external tank and space station common module structures. This process uses reverse polarity pulses to produce welds virtually free of internal defects.

Advanced weld sensor technology, comprised of machine vision-based weld seam tracking that uses both structured and global laser illumination for finding weld joints, even those difficult to discern by the human eye. Weld pool feedback is accomplished with a vision system to measure arc symmetry and molten weld pool geometry. A weld bead profiler trails the welding torch. It provides feedback to the process control system, which records quality control data.

Keywords: Welding, aluminum alloys, automation, seam tracking, sensors, profile measurement

2. INTRODUCTION

Welding for primary structures of the space program requires significant attention due to its critical role in the performance of the vehicles. This is due to a weld joint's characteristic high strength-to-weight ratio, hermetic sealing capability, and resistance to cracking over mechanical joints. Because of these considerations, the Marshall Space Flight Center has maintained an active welding development program throughout its history.

Consistent with this approach, welding development is ongoing to introduce new processes, join new materials, and improve the consistency of welds.

3. ALUMINUM WELDING

Aluminum alloys are used extensively in the structure of space vehicles primarily because of the high strength-to-weight ratio that can be obtained. Heat treated aluminum alloys commonly used in the space program can achieve the ultimate tensile strength of plain carbon steel, with only half of the weight.[1] In addition, these alloys increase in toughness at cryogenic temperatures, which makes them ideal for use for liquid oxygen and liquid hydrogen tanks.

In the space shuttle external tank, for example, the aluminum-copper alloy 2219 is used. The total length of welded joints required for fabrication is almost 800 meters for each tank produced. Since the tank is not reused, this fabrication process must be duplicated for each shuttle flight. In spite of this high volume, the full length of each weld must be inspected using x-ray and dye-penetrant inspection techniques in order to meet the service requirements for containing the volatile fuels, supporting the shuttle orbiter and solid rocket boosters, and withstanding launch loads.

Producing weld joints that meet these requirements can be a difficult undertaking. The welding process must melt the two parts and allow them to join while minimizing heat input, which maximizes the joint strength and minimizes distortion. It must avoid entraining aluminum oxides in the solidified metal and prevent formation of porosity. To do this, elaborate cleaning procedures must be followed, such as scraping the oxides from around the joint just prior to welding, and use of white cotton gloves in handling the parts. The Gas Tungsten Arc welding process has traditionally been used for these applications.

In the mid-1980's, the Variable Polarity Plasma Arc welding process was introduced into production of the external tank.[2] This welding process capitalizes on the high energy density of plasma welding coupled to a digitally-programmed current polarity waveform to bring distinct advantages to aluminum welding. It provides reduced cleaning requirements by virtue of the periodic current polarity reversals that invoke a "cathodic" cleaning effect to break up surface oxides during welding. Distortion is kept to a minimum, since the high energy of the process allows a given thickness of metal to be welded with fewer passes. Joints up to 50 mm thick can be penetrated by the plasma without requiring beveling of the joint.[3]

As a result, welding rework has been drastically reduced for the production of the shuttle external tank. Defects discovered during non-destructive examination have fallen from 8.9 per 1000" of linear weld to 1.8. This has reduced rework requirements from as many as 500 repairs per tank to less than 100, on average.

These advantages do not come without an attendant cost, however. More precise controls are required to provide the necessary settings of power input, motion, and gas flow to achieve the optimum weld. A new computer control was developed to convert from the old weld process to the new. Automation became more important as the welding process became more complex, and the welding technician was more taxed in maintaining a stable system.

4. AUTOMATION

Due to the complex nature of the welding process for aerospace applications, fabricators have learned that automation can improve weld quality by producing more consistent welds, requiring less rework.

In welding of aluminum for the external tank, critical welding parameters in the variable polarity plasma arc process are controlled by a computer system. This system executes a pre-programmed schedule of the parameters, and records the actual values for historical documentation. The welding operator is still responsible for providing real-time adjustment to weld parameters, as well as seam tracking, filler wire entry, and plasma jet orientation. Therefore, the quality and repeatability of the welds are dependent on the judgment, skill, and constant attention of the operator. A study of the causes of weld defects in the external tank revealed that most could have been prevented by intervention of an attentive operator.

Requirements for welding process control are even more stringent for new, higher performance aerospace alloys. Aluminum-Lithium alloys, such as the alloy 2195, slated for use on the external tank, provide higher strength with lower density, but are more sensitive to heat input and contamination.[6]

To address this issue, NASA has undertaken the design and development of a control system to minimize the possibility of weld defects caused by human error or oversight.[4] The system integrates multiple sensors that monitor observable process parameters with a weld process model, which provide adjustments to the process through information sent to the welding equipment controller. Major elements of this system for automation are illustrated in figure 1.

The Marshall Automated Welding System is intended to provide an integrated system for welding automation, tailored to the specific needs of individual programs. It consists of a multi-processor computer system, assembled from commercially available components, that controls the arc welding system.

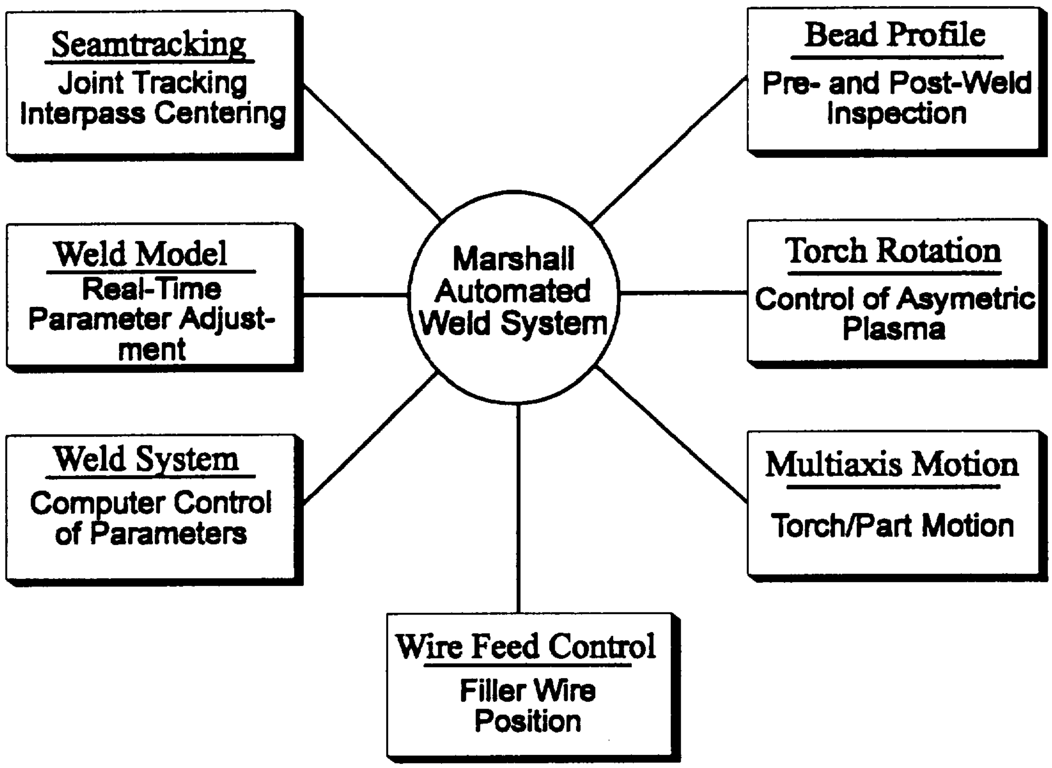

Figure 1. Major elements of the Marshall Automated Welding System

As the needs for advanced sensors, motion control, and weld process control are identified, additional computer and sensor controllers can be added to meet those needs, while assuring the coordination of the control system response. In this way, appropriate levels of technology can be applied to the welding task, and improvements in technology and understanding can be incorporated as they become available.

5. SENSORS

Due to the special needs of external tank welding of aluminum, NASA has developed a sensor system to address the specific requirements of production welding.[5] The elements of this system are described below:

5.1 Seam tracking

The welding torch must be centered over the weld seam to provide proper fusion of the two pieces of metal. A slight offset may result in an area where one piece does not completely fuse to the other. Defects of this nature are readily detected by non-destructive examination, but require expensive repairs. In welding of configurations encountered on the external tank, the root bead must be kept within 1.5 mm of the joint to make acceptable welds. In addition, tracking of each successive welding pass must be placed properly on top of the previous one.

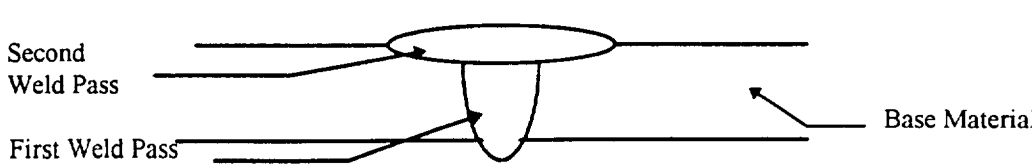

Figure 2. Cross-sectional View of Weld Bead, Showing Two-Pass Weld

5.2 Stereo Seam Tracking Sensor

A seam tracking sensor system has been developed to address the specific needs of welding on the shuttle external tank. The system uses innovative illumination techniques, coupled with gray-scale processing on a stereo pair of images to deduce seam location. This approach is intended to detect the seam in spite of the high reflectivity of machined aluminum, and without requiring a groove or other three-dimensional feature, as in conventional seam tracking sensors. The result is a sensor capable of providing three-dimensional position information from a single video frame of information.

Pulsed lasers of 180-watts peak power are used for illumination of the area 50 mm ahead of the torch. A split screen "torch view" gives the operator remote viewing capability of the leading edge of the weld pool. This will be used to track the edges of the first weld pass during welding of the second pass, while improving the operator's ability to view the arc and the filler wire placement.

The video from this sensor is split into halves. The top half shows a left and right binocular view of the weld joint, for seam tracking. The bottom half of the image gives a view of the leading edge of the weld pool around the shield cup of the torch, with the filler wire feeding down through the center of the image, as shown below:

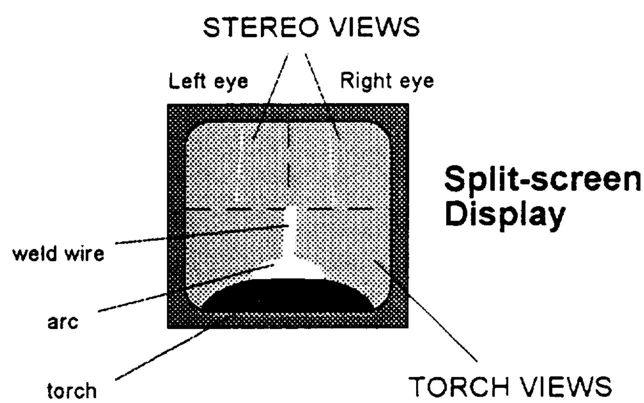

Figure 3. Illustration of Seam Tracking Sensor Video Display

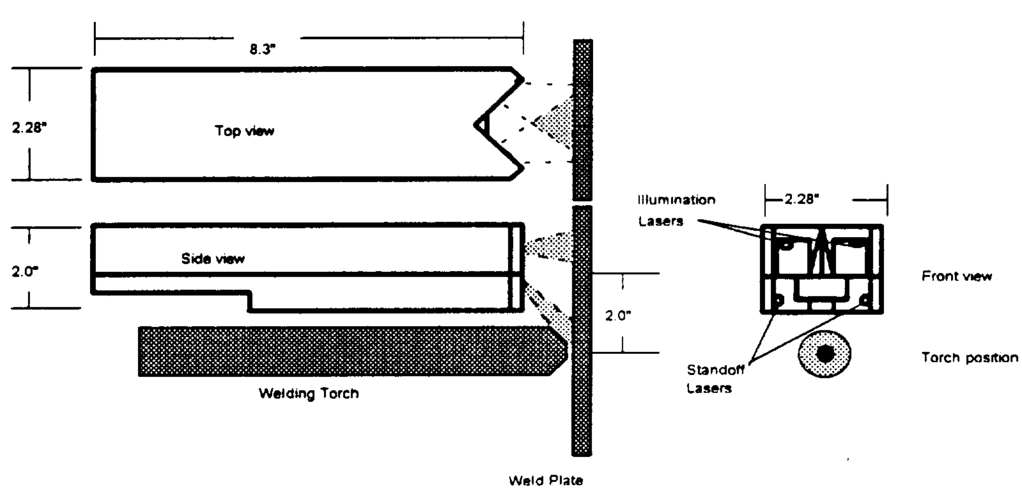

Figure 4. Mechanical specifications of Seam Tracking Sensor, Illustrating Two Fields-of-View

In tests at the Marshall Space Flight Center in 1993, the seam tracking sensor was tested on sample plates intended to demonstrate application to production situations. In these tests, the sensor demonstrated a worst-average Y error (across the seam) of 0.13 mm. The worst average Z-error (above the seam) was less than 0.1 mm.

5.3 Bead Profile Measurement

The welding technician monitors the shape of the solidified bead during automatic welding, and adjusts the process to compensate for irregularities. One situation is "lack of fill," where the bead does not achieve adequate level of reinforcement, which can be corrected by increasing filler wire feed rate, or changing the weld heat input. Another situation is "asymmetry," where a skew of the plasma arc causes one side of the solidified weld bead to be lower than the other, corrected by rotating the weld torch.

A weld bead profiling sensor has been developed that can detect the above conditions, and provide information back to the welding control system to adjust, during the weld, to avoid exceeding the tolerance for these conditions. Measurements can be made to record how well the parts fit before welding. Similarly, it can be used to record the resulting solidified weld bead profile, verifying weld quality.

The sensor uses structured laser light and a CCD camera to record and analyze:

Crown height	Height of weld bead above surface of parent metal
Peaking	Intersection angle of parts being joined
Mismatch	Offset of parts being joined
Undercut	Depth of weld bead below surface of parent metal
Weld Width	Width of weld reinforcement

These measurements are illustrated in the profile below, in the case where the bead lacks positive reinforcement:

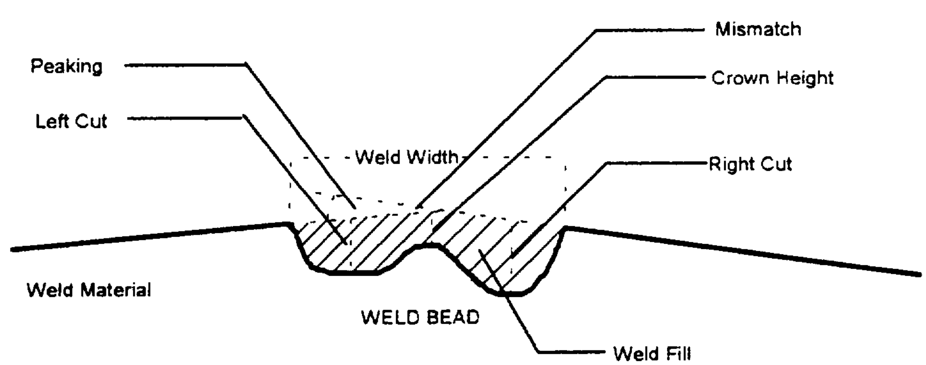

Figure 5. Illustration of bead profile measurements

In tests at the Marshall Space Flight Center, the sensor was used to measure ten weld samples, which were then cross-sectioned and measured on a shadow-graph. The results are recorded on the table below:

Measurement Type	Average Error	Single Maximum Error	Resolution(calculated)
Left Undercut	0.08 mm	0.18 mm	0.08 mm
Right Undercut	0.05 mm	0.08 mm	0.05 mm
Crown Height	0.08 mm	0.15 mm	0.08 mm

Mismatch	0.01 mm	0.2 mm	0.1 mm
Peaking	0.64 deg.	1.56 deg.	0.64 deg.

Table 1. Sensor measurement test results

The sensor measures how well the parts fit before welding, as illustrated below. Gap and offset measurements are estimated to be resolvable to 0.1 mm.

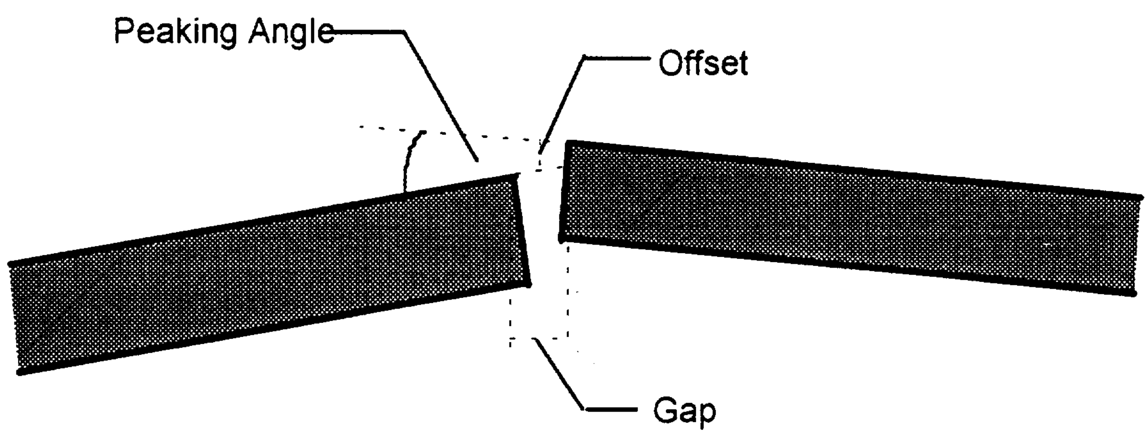

Figure 1. Pre-Weld Part Fit-Up Measurements

5.4 Weld Pool Monitoring

Preliminary testing has been completed on a newly-developed welding sensor that monitors the weld molten pool, to provide collection of real-time information about the quality of the weld. The sensor mounts directly behind the torch, with the optic axis looking into the rear of the weld at an angle of 30 degrees off vertical, as shown in figure 7.

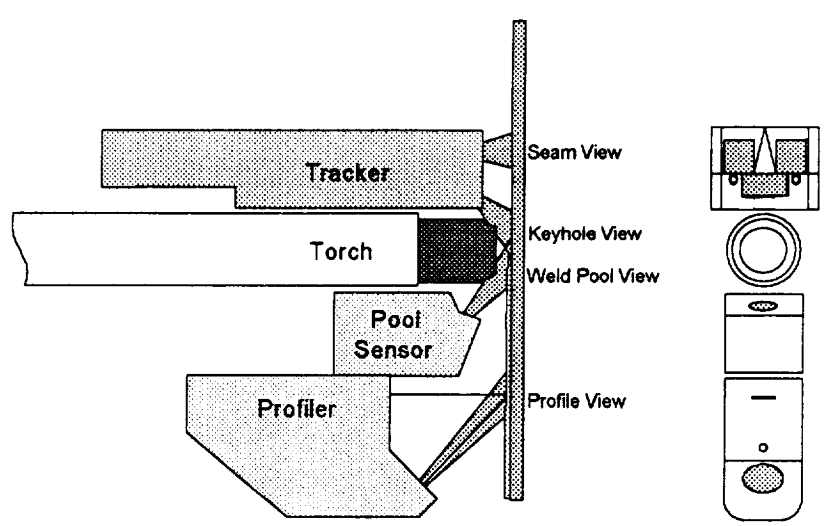

Figure 7. Illustration of sensor suite, mounted about the welding torch

This angle affords a view of the arc, torch tip, and lower edge of the plasma keyhole, as well as the first inch of the solidified weld bead as it exits from under the weld torch. Neutral density filters, along with a computer-controlled electronic shutter in the camera, are used to adjust image exposure so that the brightest part of the arc will be just below camera saturation. An illustration of the video image from this sensor is diagrammed below:

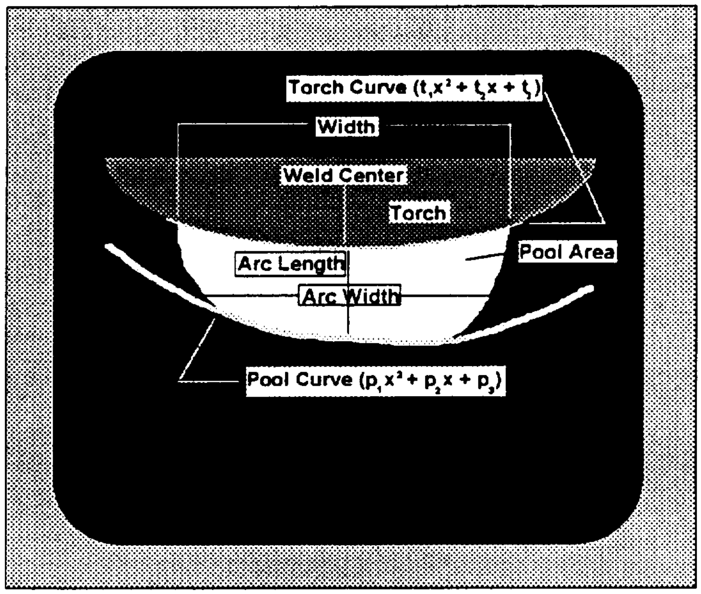

Figure 8. Diagram of Weld Pool Sensor Video Image

The goal of this sensor development is to enhance the operation of the seam tracker and weld bead profiler by measuring the following parameters:

Pool Curvature

The line that is formed as the weld pool solidifies is characterized for symmetry, providing fast response to the onset of plasma skew.

Weld width, Arc Length, Arc Width, Pool Area

These parameters of the weld are monitored, to be used by the weld model to provide accurate control of weld bead geometry, critical to achieving the highest possible weld strength.

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This will enhance the operation of the seam tracker by assuring that the arc is aligned with the weld seam, rather than the torch central axis, countering any misalignment due to plasma arc skew.

6. TECHNOLOGY TRANSFER

The sensor technology developed under this program has found application outside welding programs for NASA, and even beyond those for aerospace manufacturing.

One implementation of this technology outside NASA was to automate welding for a local air conditioning compressor manufacturer. The manufacturer had mechanized the operation of a Gas Metal Arc welding system for completing the girth weld on the metal housing of the compressor unit. While this mechanization was considered successful, the sensor technology was pursued because specific advantages that the system was capable of providing, which included:

Control of torch cross-seam and standoff position regardless of compressor size or shape
Measurement of pre-weld gap, allowing adjustment of parameters for individual compressors
Control of welding speed at the torch, to compensate for out-of-round conditions
Archival of system welding performance
Flexibility in configuration and setup

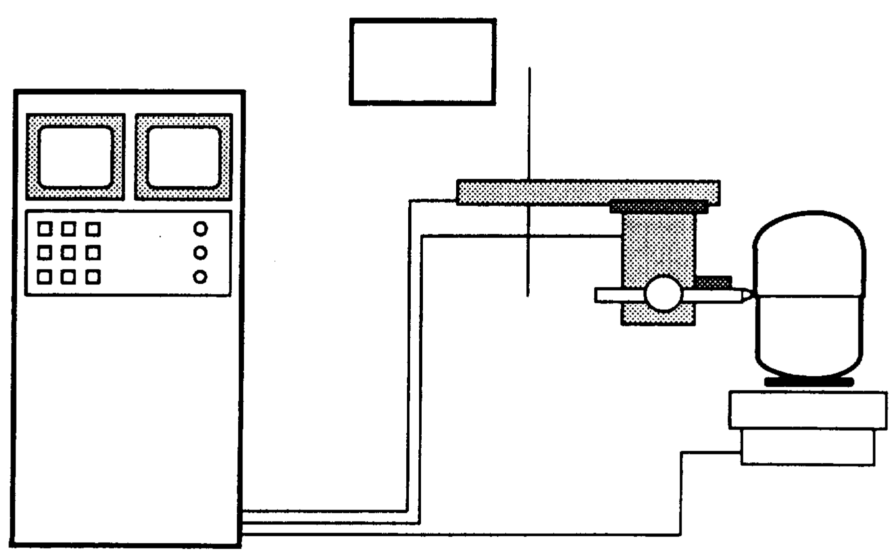
A system to meet these objectives was co-developed by NASA, Applied Research, Inc., and Martin-Marietta. It was based on the weld profiling sensor that had been designed for measuring the solidified weld bead on arc welds for the space shuttle external tank.

The system was designed and tested on prototype parts at the Marshall Space Flight Center's Productivity Enhancement Complex. After successful demonstration for the local industry, it was installed in the compressor plant for demonstration and successfully welded for an 8 hour shift (approximately 520 compressors). The following features were demonstrated:

Features	Status
Cross-seam and standoff seam position measurement	Demonstrated
Pre-weld gap measurement	Demonstrated
Cross-seam and standoff torch position control	Demonstrated
Circular turntable positioning	Feasible
Weld speed monitoring	Demonstrated
Weld speed control	Feasible
Weld parameter control (voltage, wire feed)	Feasible
Operator pendant for setup and compressor selection	Demonstrated
User interface screens for system configuration and operation	Demonstrated
System performance data archival and statistics	Demonstrated

Table 2. Compressor Welding Automation System Features And Status

A block diagram of the system is shown below:



7. SUMMARY

Welding automation becomes increasingly important for welds in critical performance applications. New, high-performance metal alloys may require process controls beyond what conventional, human-controlled systems can provide in a cost-effective manner.

To this end, a control architecture has been defined that allows incorporation of sensors to the welding system as they are needed, and provides a means of information exchange between functions in the system, to improve the ability to control effectively.

Three sensors have been described that allow tracking seams and measuring critical weld geometries visually through images with low signal-to-noise ratios. These sensors have been applied to prototype production applications for the space shuttle external tank, and in a high-speed commercial welding application.

This technology is available for adaptation to commercial process automation and measurement tasks, through a cooperative development program with NASA's Marshall Space Flight Center

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Flinn, R.A., Trojan, P.K., *Engineering Materials and Their Applications*, pp.142,178, Houghton Mifflin Co., Boston, MA, 1975.

2. Nunes, A.C., et. al., "The Variable Polarity Plasma Arc Welding Process: Its Application To The Space Shuttle External Tank - First Interim Report," NASA TM-82532, June, 1983.

3. Nunes, A.C., et. al., "The Variable Polarity Plasma Arc Welding Process: Its Application To The Space Shuttle External Tank - Second Interim Report," NASA TM-86482, November, 1984.

4. Lawless, K.G., "Fully Automated Variable Polarity Plasma Arc Welding," *Research and Technology 1992, Annual Report of the Marshall Space Flight Center*, page 170, NASA TM-103599, 1992.

5. Powell, B.W., Burroughs, I.A., "Active Weld Control," Final Report, NASA Contract no. NAS8-38551, January, 1994.

6. Cross, C.F., Tack, W.T., "Selection and Weldability of Aluminum-Lithium Alloys," *ASM Handbook, Volume 6*, pp. 549-553, December, 1993.

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Abstract

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Variable Polarity Plasma Arc Welding (VPPA) - High Quality Aluminum Welding Process utilized for fabrication of the Space Shuttle External Tank and Space Station. This process utilizes reverse cycle pulsing for internally defect free welds.

Advanced Weld Sensor Technology - Machine Vision Based Weld Seam Tracking utilizing both structured and global laser light for finding weld joints even difficult to discern by human eye. Weld pool feedback is also accomplished utilizing a vision based system to determine arc symmetry and arc geometry. A bead profiler utilizing structured laser light trails the weld producing quality control data and feedback to the other sensors.